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A WIND POWER PLANT AND A METHOD FOR CONTROL

FIELD OF THE INVENTION

This invention relates to a wind power plant comprising at least one wind power station, which includes a wind turbine, an electric generator driven by this wind turbine, and an electric alternating voltage connection connecting the wind power station with a transmission network or distribution network. The invention also relates to a method for control in such a wind power plant.

The invention is preferably intended to be used in such cases where the connection between the generator and the transmission or distribution network includes a cable intended to be submerged into water. Consequently, expressed in other words, it primarily relates to such applications where one or several wind turbines with associated generators are intended to be placed in seas or lakes, wherein the cable connection extends to the transmission or distribution network placed on land. Even though the advantages of the invention in the following primarily will be dealt with in connection with location of the wind turbines in seas or lakes, the invention can, however, also imply advantages in cases where the wind turbines and the generators are located on land and the connection, which in that case not necessarily has to consist of a cable but instead can be realized in the form of aerial lines or cables, connects several such wind

turbines/generators with the transmission or distribution network.

BACKGROUND OF THE INVENTION AND PRIOR ART

When locating wind power at sea it is required, in order to get economy in the project, that large groups of wind power stations are being located within a limited area. Sea based wind power requires relatively large wind power stations (3MW and above) and a suitable total system power of 50-100 MW is expected. So far the planning of such wind parks has presupposed that the electrical power transmission is effected by traditional alternating current transmission in three-phase alternating voltage sea cable systems. In that case, the generator is almost always a three-phase asynchronous generator. It is true that there are examples where synchronous generators have been used directly connected to the network, but this has as a rule resulted in that a complicated mechanical spring suspension has had to be installed between the generator and the engine house in order to dampen power variations caused by the varying character of the wind load. This depends on the fact that the rotor dynamics of a synchronous generator mechanically behaves like a spring against a stiff alternating voltage network, whereas an asynchronous generator behaves like a damper. A conventional asynchronous generator of 3 MW could presumably be made for about 3-6 kV and be connected in series with a transformer which steps up the voltage to, let us say 24 kV, in a first step. In a wind power park with 30-40 wind power stations there would then be provided a central transformer which further steps up the voltage to 130 kV. The advantage with such a system is that it is cheap and does not require any complicated sub-systems. The disadvantage partly lies in the difficulties to technically transmit power over long distances in a high-voltage alternating voltage cable. This depends on the fact that the cable produces capacitive reactive power, which increases with the length. The current through the conductor and in the cable shield then in-

creases so much that the cable cannot be realized for long distances. The other disadvantage lies in that the varying wind load causes voltage variations on the transmission line, which could affect the power consumers that are connected nearby. This applies in particular if the network is "weak", i.e. has a low short-circuiting power. Due to the abovementioned technical problems with long cable transmission distances, one might be forced to connect the wind park to a "weak" network. According to certain guiding principles, the voltage variation may not be more than 4%. Different countries have different regulations and as a rule the regulations are mitigated in case of a lower voltage level on the transmission line. Voltage variations could also have to be treated differently depending on time intervals. Rapid voltage variations causes "flicker", i.e. light variations in glow lamps, which is regulated in rules.

A solution, lying at the side of the present invention, concerning the abovementioned problems with long cable distances is to transmit the power with high-voltage direct voltage. The cable can then be drawn right up to a strong network. Another advantage is that DC-transmissions have lower losses than AC-transmissions. From a technical point of view the cable distance can then be of unlimited length. A HVDC-link consists of a rectifier station, a transmission line (cable or aerial line), an inverter station and filters for removing overtones generated during the conversion. In an older variant of HVDC-links thyristors are used for rectification and inversion. Thyristors can be switched on but not switched off: the commutation takes place at the zero-crossing of the voltage, which is determined by the alternating voltage, and the converters are therefore called line commutating. A disadvantage with this technique is that the converters consume reactive power and cause current overtones, which are sent out in the network. In a more modern direct voltage solution, IGBT:s are used instead of thyristors in the converters. An IGBT (Insulated Gate Bipolar Transistor) can be switched on as well as switches off and furthermore has a high switch fre-

quency. This implies that the converters can be produced according to a completely different principle. so called self-commutating converters. To sum up, the advantages with self-commutating converters are that they can deliver as well as consume reactive power, which makes possible an active compensation of the voltage level on the network side if the network is weak. Consequently, this makes this type of converter superior to the older technique in the way that it can be connected to a network being situated closer to the wind power. The high switch frequency also leads to a reduction of the problem with overtones as compared with the older generation of HVDC. A disadvantage is, however, that the losses in the converter station are higher as well as the price. A self-commutating converter is characterized in that the voltage is built up by a rapid pulse pattern, which is generated by the converter. The voltage difference between the pulse pattern and the sinusoidal network voltage will lie above the inductances on the network side. There are two types of self-commutating inverters; a voltage stiff, VSI (Voltage Source Inverter) and a current stiff, CSI (Current Source Inverter), with somewhat different characteristics. VSI, which has at least one capacitor on the DC-side, has the best power regulation.

There have been built some experimental wind power stations using technique resembling the HVDC-concept, but for a completely different reason, namely for achieving a variable rotational speed of individual wind power stations. The generator of the wind power station is then disconnected from the network via a DC-link on low voltage, typically the 400 V or 660 V level. A variable rotational speed on the turbine gives energy gains at the same time as it as a rule results in that the variations of the rotational speed can be used for eliminating the rapid power pulsations, which cause "flicker". However, it is of course not possible to eliminate the slow power changes, which are inherent in the nature of the wind load. The moment of inertia of the turbine could be said to function as an intermediate storage for

kinetic energy. In such a system a synchronous generator is not to any disadvantage, but rather to an advantage, since the asynchronous generator requires a more expensive and more complicated rectifier. If it is desired to have a direct driven generator and consequently eliminate the need of a gear unit between the turbine and the generator, the generator must be synchronous since it will be provided with so many poles. In other words, a direct driven generator requires a DC-intermediate link. In the concept it is also possible to actively regulate the moment by changing the trigger angle, if a controlled rectifier is used. In most concepts having a variable rotational speed, an external active rotational speed control is furthermore provided by so called pitch control, which implies that the blade angle is changed on the turbine. A disadvantage with a variable rotational speed according to the related concepts is the price of the required power electronics and furthermore that the maintenance of such power electronics out at sea will be difficult and costly.

PURPOSE OF THE INVENTION

The purpose of the present invention is to achieve, with deviation from the abovementioned direct voltage connections, an alternating voltage connection between a particularly sea based wind park and a particularly land located transmission or distribution network. with the possibility of considerably longer transmission distances and lower losses than what is offered by a conventional alternating voltage connection, and at the same time create the possibility for operation with a variable rotational speed without any power electronics at all out at sea. This is very valuable. since all maintenance taking place at sea is expensive and difficult to perform. A further purpose with the invention is to achieve the same good regulation possibilities concerning reactive power as offered by a modern HVDC-system.

SUMMARY OF THE INVENTION

The purpose of the invention is primarily achieved in that a frequency converter is connected to the electrical alternating voltage connection on the network side of the plant, which frequency converter is arranged to fix the frequency of the connection between the wind power station and the converter to be essentially below the network frequency and to convert this low frequency of the connection into correspondence with the higher frequency of the network. The expression "on the network side of the plant" consequently means that the frequency converter is located relatively close to the transmission or distribution network, whereas the principle part of the connection extends between the frequency converter and the wind power station itself, for instance in the form of a submarine cable. Consequently, this implies that the transmission in the connection essentially will take place at a low frequency, and consequently prerequisites of considerably longer transmission distances and lower losses are created than offered by a conventional alternating voltage connection with regular network frequency. Normally occurring network frequencies are in the level from 50 to 60 Hz. If the low frequency in the alternating voltage connection between the frequency converter and the wind power station for instance is 10 Hz, the capacitive current in a cable is reduced 5 times for the same voltage as in a 50 Hz network. This implies that distances being 5 times as long can be connected with for instance a submarine cable.

A further advantage of the inventional idea is that the frequency converter consequently will be located close to the transmission or distribution network, i.e. normally on land, which drastically reduces the costs for maintenance and supervision and also reduces the duration of service interruptions in case of breakdowns.

According to a preferred embodiment of the invention, several wind power stations with asynchronous generators are interconnected parallelly with the alternating voltage connection. The suitable frequency and voltage of the alternating voltage connection depends on the size of the wind park and the distance from land, but for a 50 MW wind park a frequency of 10-20 Hz at 130 kV should be suitable.

According to an embodiment of the invention, the frequency converter comprises a direct voltage intermediate link with an AC/DC-converter and an inverter arrangement. This makes it possible to put a variable frequency as well as a variable voltage on the low-frequency alternating voltage connection. In particular it is then preferred that a DC/DC-converter is comprised in the direct voltage intermediate link. Even though, in a preferred embodiment, valves in the frequency converter consist of IGBT:s connected in series, other types of valves would be possible to use. Also other types of frequency converters, for instance direct converters, also called "cyclo converters", which lack a direct voltage link, can be used with the invention as well as also other frequency converters than static ones, i.e. also rotary frequency converters. According to embodiments, dealt with in more detail later on, at least one transformer can be arranged on the generator side of the connection for step-down transformation of the voltage of the alternating voltage connection between the generator and the frequency converter to a suitable generator voltage level. In that case, each of the occurring generators can be provided with its own transformer, in addition to which as a complement or an alternative thereof, a transformer being common for all generators can be provided. Consequently, such transformers make it possible to increase the voltage in the alternating voltage connection to a higher level than conventional generators are capable of. A disadvantage of such transformers is that they imply an extra cost and also entail the deficiency that the total effectivity of the system is reduced. They also imply a risk of fire and a risk for the envi-

ronment since they contain transformer oil, which can leak out in case of breakdown or vandalism.

With the generator technology of today concerning wind power stations, it is possible to produce a generator which can handle 10 kV, but higher voltages than that would be desirable. Furthermore, the conventional insulation technology for stator windings is sensitive to temperature variations, humidity and salt, which a wind turbine generator is exposed to.

According to a particularly preferred embodiment of the invention, a solid insulation is used for at least one winding in the generator, which insulation preferably is performed according to the subsequent claim 14. The winding has more specifically the character of a high-voltage cable. A generator manufactured in this way, creates the prerequisites of achieving considerably higher voltages than conventional generators. Up to 400 kV can be achieved. Furthermore, such an insulation system in the winding implies insensibility to salt, humidity and temperature variations. The high output voltage implies that transformers can be completely excluded, which implies avoidance of the already mentioned disadvantages of such transformers.

A generator having such a winding formed by a cable can be produced by threading the cable in slots performed for this purpose in the stator, whereupon the flexibility of the winding cable implies that the threading work can be easily performed.

The two semiconducting layers of the insulation system have a potential compensating function and consequently reduce the risk of surface glow. The inner semiconducting layer is to be in electrically conducting contact with the electrical conductor, or a part thereof, located inwardly of the layer, in order to obtain the same potential as this. The inner layer is intimately fastened to the solid insulation located outwordly thereof and this also applies to the fastening of the outer semiconducting layer to the

solid insulation. The outer semiconducting layer tends to contain the electrical field within the solid insulation.

In order to guarantee a maintained adherence between the semiconducting layers and the solid insulation also during temperature variations, the semiconducting layer and the solid insulation have essentially the same thermal coefficient of expansion.

The outer semiconducting layer in the insulation system is connected to ground potential or otherwise a relatively low potential.

In order to achieve a generator capable of very high voltage, the generator has a number of features which have already been mentioned above and which distinctly differ from conventional technology. Further features are defined in the dependent claims and are discussed in the following:

Features which have been mentioned above and other essential characteristics of the generator and consequently of the wind power plant according to an embodiment of the invention comprise the following:

- The winding in the magnetic circuit is produced of a cable having one or several permanently insulated electrical conductors with a semiconducting layer at the conductor and outwardly of the solid insulation. Typical cables of this kind are cables having an insulation of cross-linked polyethylene or ethylene-propene, which for the purpose here in question are further developed concerning stands of the electrical conductor and also the character of the insulation system.

- Cables having a circular cross section are preferred, but cables having another cross section can also be used for instance in order to achieve a better packing density.

- Such a cable makes it possible to design a laminated core of the magnetic circuit in a new and optimai way as concerns slots and teeth.

- Advantageously, the winding is produced with a stepwise increasing insulation for the best utilization of the laminated core.

- Advantageously, the winding is produced as a concentric cable winding. which makes it possible to reduce the number of coil end crossings.

- The shape of the slots is adapted to the cross section of the winding cable so that the slots are in the form of a number of cylindrical openings extending axially and/or radially outwardly of each other and having constrictions running between the layers of the stator winding.

- The shape of the slots is adapted to the cable cross section in question and to the stepwise changing thickness of the insulation of the winding. The stepwise insulation makes it possible for the magnetic core to have an essentially constant tooth width independent of the radial extension.

- The abovementioned further development concerning the stands impiies that the winding conductor consisting of a number of layers brought together, i.e. insulated strands, does not necessarily have to be correctly transposed, non-insulated and/or insulated from each other.

- The abovementioned further development concerning the outer semiconducting layer implies that the outer semiconducting layer is cut off at suitable points along the length of the cable and each cut-off partial length is directly connected to ground potential.

The use of a cable of the type described above makes it possible that the hole length of the outer semiconducting layer of the cable, as well as other parts of the plant, can be kept at ground potential. An important advantage is that the electrical field is close to zero in the coil end region outwardly of the outer semiconducting layer. With ground potential on the outer semiconducting layer the electric field does not have to be controlled. This implies that there will occur no field concentrations neither in the core, nor in the coil end regions or in the transition section between them.

The mixture of insulated and/or non-insulated strands packed together, or transposed strands, results in low eddy current losses. The cable can have an outer diameter in the order of 10-40 mm and a conductor area in the order of 10-200 mm^2.

Furthermore, the invention comprises a method for controlling the operation of a wind power plant according to the subsequent claims.

BRIEF DESCRIPTION OF THE DRAWINGS

With reference to the subsequent drawings, a closer description of embodiments of the invention given as examples will follow below. In the drawings:

Fig 1 is a schematic axial end view of a sector of the stator in an electric generator in the wind power plant according to the invention.

Fig 2 is an end view, partly cut, of a cable used in the stator winding according to Fig 1,

Fig 3 is a schematic view, partly in section, of an embodiment of a wind power generator according to the invention,

Fig 4 is a schematic view showing the embodiment of the wind power plant according to the invention,

Fig 5 is likewise a schematic view illustrating an alternative embodiment of the plant,

Fig 6 is a view similar to Fig 5 of a variant, and

Fig 7 is a view illustrating a possible embodiment of the frequency converter comprised in the plant.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

With the aid of Figs 1-3 the design of the generator 1 preferred in an embodiment of the invention is first explained. Fig 1 shows a schematic axial view through a sector of the stator 2. The rotor of the generator is denoted as 3. The stator 2 is in a conventional way formed of a laminated core. Fig 1 shows a sector of the generator corresponding to a pole pitch. From a yoke section of the core, located furthest out in radial direction, a number of teeth 5 extend radially inwards towards the rotor 3 and these teeth are separated by a slot 6, in which the stator winding is arranged. Cables 7 forming this stator winding are high-voltage cables which can be of essentially the same type as those used for power distribution, i.e. PEX-cables (PEX = cross-linked polyethylene). A difference is that the external mechanically protecting PVC-layer and the metal shield normally surrounding such a power distribution cable have been eliminated so that the cable for the present invention only comprises the electrical conductor and at least one semiconducting layer on each side of an insulating layer. The cables 7 are schematically illustrated in Fig 1, wherein only the electrically conducting central part of each cable section or coil side is shown. It appears that each slot 6 has a varying cross section with alternating broad parts 8 and narrow parts 9. The broad parts 8 are essentially circular

and surround the cable, waist sections between the broad parts forming the narrow parts 9. The waist sections serve to radially fix the position of each cable. The cross section of the slot 6 becomes narrower radially inwards. This depends on that the voltage in the cable sections are lower the closer they are situated to the radially innermost part of the stator 1. Thinner cables can therefore be used inwards, whereas thicker cables are required further out. In the illustrated example, cables with three different dimensions and arranged in three correspondingly dimensioned sections 10, 11, 12 of the slot 6 are used. A winding 13 for auxiliary power is arranged furthest out in the slot 6.

Fig 2 shows a stepwise cut end view of a high-voltage cable for use in the generator. The high-voltage cable 7 comprises one or several electrical conductors 14, each of which comprises a number of strands 15, which together give a circular cross section. The conductors can for instance be of copper. These conductors 14 are arranged in the middle of the high-voltage cable 7 and in the shown embodiment each of the conductors is surrounded by a partial insulation 16. It is however possible to omit the partial insulation 16 on one of the conductors 14. In the shown embodiment the conductors 14 are surrounded by a first semi-conducting layer 17. Around this first semiconducting layer 17 there is an insulation layer 18, e.g. of PEX-insulation, which in its turn is surrounded by a second semiconducting layer 19. Consequently, the concept "high-voltage cable" does not, in this application, have to comprise any metal shield or any external protective layer of the type normally surrounding a power distribution cable.

In Fig 3 a wind power station is shown with a magnetic circuit of the type described with reference to Figs 1 and 2. The generator 1 is driven by a wind turbine 20 via a shaft 21. Even though the generator 1 can be direct driven by the turbine 20, i.e. that the rotor of the generator is coupled fixed in rotation to the shaft of the turbine 20, there can be a gearing 22 between the turbine 20

and the generator 1. This can for instance be constituted by a single-step planetary gearing, the purpose of which is to change up the rotational speed of the generator in relation to the rotational speed of the turbine. The stator 2 of the generator carries the stator windings 23, which are built up of the cable 7 described above. The cable 7 can be unsheathed and pass on into a sheathed cable 24 via a cable joint 25.

In Fig 4, which in a schematic form broadly illustrates the wind power plant, two wind power stations 29 connected in parallel are illustrated, each having a generator. The generator has a field winding 26 and one (or several) auxiliary power windings 27. In the shown embodiment the generators are Y-connected and the neutral point is grounded via a respective impedance 28.

In Fig 4 the two wind power stations, embracing generator 1 as well as (not shown) wind turbine, are generally denoted as 29. An electric alternating voltage connection 30 connects the two wind power stations 29 to a transmission or distribution network 31. This is here of three-phase type. The normal frequency of such a network is 50 or 60 Hz. The connection 30 comprises, along a section denoted as 32, a cable 33 intended to be submerged into water. However, instead of a cable submerged into water, one or several aerial lines/cables could also come into question. The section 32 can in practice be very large.

On the network side of the plant a frequency converter 34 is connected to the electrical alternating voltage connection 30, which frequency converter is arranged to fix the frequency of the connection between the wind power station 29 and the converter 34 to be substantially below the frequency of the network 31 and to convert this low frequency of the connection into correspondence with the higher frequency of the network 31.

As appears from the previous description, the generator 1 is of asynchronous type in the example.

The frequency converter 34 is suitably located on land in a suitable station nearby the network 31. The wind power stations 29 are located out at sea or a lake on suitable foundations. On one of these foundations, or on a foundation particularly set ups for this purpose, the outgoing cables from the generators 1 are interconnected, e.g. via bus-bars, in a point denoted as 35.

In Fig 4 it is illustrated how a circuit breaker 36 is provided between the frequency converter 34 and the network 31 and sets of disconnectors on each side thereof.

In the embodiment according to Fig 4 the generators 1 are direct coupled to the frequency converter 34. This is a consequence of the fact that the generators 1 are supposed to be of the design described above with reference to Figs 1 and 2, i.e. capable of generating a very high voltage.

In the variant according to Fig 5, it is illustrated how a transformer 31, common for the generators 1, is arranged between the parallel connection point 35 for the generators 1 and the frequency converter 34, which transformer is intended to achieve a high voltage in the part of the connection situated between the transformer and the frequency converter 34 and a comparatively lower voltage between said transformer 38 and the generators 1. This common transformer 38 is located on the wind power side of the connection 30, i.e. close to the wind power station 29. so that the main part of the connection 30 will be present between the transformer 38 and the frequency converter 34. Suitably the transformer 38 can be placed on one of the foundations for the wind power stations 29 or possibly on its own foundation on a strategic place.

The variant in Fig 6 illustrates an alternative corresponding to the one in Fig 5 with the exception that a particular transformer 39 is here arranged for each of the generators 1. Consequently, the wind power stations are parallelly interconnected in the point 35 only after these transformers. In such an embodiment, it would be possible to omit the transformer 38. which has been more closely described with reference to Fig 5. Further, it is also possible to keep the transformer 38 so that the voltage from a single wind power station will be stepped up in two steps, i.e. at first via the transformer 39 and then by means of the common transformer 38.

In Fig 7 a possible embodiment of the frequency converter 34 is illustrated. It here includes a direct voltage intermediate link having a AC/DC-converter 40 and an inverter 41. In the direct voltage intermediate link a DC/DC-converter 42 is advantageously included. The inverter 41 is a voltage stiff self-commutated inverter. Over the DC-link of the inverter a capacitor is parallel connected. Network inductances 44 are connected in series in each phase on the alternating voltage side of the inverter 41.

The inverter 41 suitably comprises an IGBT 45.

The AC/DC-converter can be built up like the inverter 41 and has on its AC-side network inductances 46 in series in each phase. The converter 40 can comprise an IGBT 47. On the DC-side there is a capacitor 48 connected in parallel with the IGBT.

The plant has means (not shown) for measuring the active power from the wind power plant and means for measuring the present wind speed. These measuring means are connected to a control unit comprised in the frequency converter 34, which control unit controls the frequency regulation depending on the prevailing measuring values. In that connection, the control unit can be arranged to control the frequency of the connection 30 in correspondence with an ideal characteristic over the rotational

speed of the wind turbine as a function of wind speed. Such a frequency control can be denoted as "slow". It is based on that the rotational speed of the wind power stations preferably should rise linearly with the wind speed up to the maximum rotational speed. With knowledge about the wind speed, a comparatively slow frequency control can consequently take place in the connection 30 so that the most favourable conditions ensue.

The control unit is furthermore suitably arranged to control the frequency of the connection 30 by comparison of measured transmitted active power with an ideal characteristic over the rotational speed as a function of power. Such a frequency control can here popularly be denoted as "fast". It is conducted with the aim of rapid power variations and this can e.g. be achieved with PI-regulation and regeneration of the transmitted power through the DC-link, as described with reference to Fig 7.

As far as the voltage regulation in the connection 30 is concerned, this is suitable carried out in the most simple way so that the control unit is made to control the frequency converter 34 to maintain a constant ratio voltage/frequency of the connection over the major part of the frequency range.

The invention is of course not only limited to the described embodiments. Several detail modifications are consequently possible and realized by men skilled in the technical field as soon as the basic inventional idea has been presented. Such detail modifications and equivalent embodiments are included within the scope of the subsequent claims.